A Retrospective Multicenter Study Comparing Speech Perception Outcomes for Bilateral Implantation and Bimodal Rehabilitation

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Objectives: To compare speech perception outcomes between bilateral implantation (cochlear implants [CIs]) and bimodal rehabilitation (one CI on one side plus one hearing aid [HA] on the other side) and to explore the clinical factors that may cause asymmetric performances in speech intelligibility between the two ears in case of bilateral implantation.

Design: Retrospective data from 2247 patients implanted since 2003 in 15 international centers were collected. Intelligibility scores, measured in quiet and in noise, were converted into percentile ranks to remove differences between centers. The influence of the listening mode among three independent groups, one CI alone (n = 1572), bimodal listening (CI/HA, n = 589), and bilateral CIs (CI/CI, n = 86), was compared in an analysis taking into account the influence of other factors such as duration of profound hearing loss, age, etiology, and duration of CI experience. No within-subject comparison (i.e., monitoring outcome modifications in CI/HA subjects becoming CI/CI) was possible from this dataset. Further analyses were conducted on the CI/CI subgroup to investigate a number of factors, such as implantation side, duration of hearing loss, amount of residual hearing, and use of HAs that may explain asymmetric performances of this subgroup.

Results: Intelligibility ranked scores in quiet and in noise were significantly greater with both CI/CI and CI/HA than with a CI-alone group, and improvement with CI/CI (+11% and +16% in quiet and in noise, respectively) was significantly better than with CI/HA (+6% and +9% in quiet and in noise, respectively). From the CI/HA group, only subjects with ranked preoperative aided speech scores >60% performed as well as CI/CI participants. Furthermore, CI/CI subjects displayed significantly lower preoperative aided speech scores on average compared with that displayed by CI/HA subjects. Routine clinical data available from the present database did not explain the asymmetrical results of bilateral implantation.

Conclusions: This retrospective study, based on basic speech audiometry (no lateralization cues), indicates that, on average, a second CI is likely to provide slightly better postoperative speech outcome than an additional HA for people with very low preoperative performance. These results may be taken into consideration to refine surgical indications for CIs.

Key words: Asymmetry, Bilateral, Bimodal, Binaural, Hearing aid, Hearing loss, Plasticity, Pure-tone average.

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INTRODUCTION

Surgical indications for cochlear implantation have expanded since the 1990s. In earlier times, unilateral implantation was the standard for adults and children with bilateral profound deafness (National Institutes of Health Consensus Conference 1995), and the use of the contralateral hearing aid (HA) was not recommended, at least until 1990 for adults (Dooley et al. 1993). In contrast, nowadays, ipsilateral hearing preservation during surgery is the gold standard (Fraysse et al. 2006; Friedland & Runge-Samuelson 2009; Skarzynski et al. 2010). Adding the low-frequency input from an ipsilateral (hybrid stimulation) or contralateral HA (bimodal rehabilitation) is recommended to improve speech comprehension and spatial localization performance (Most et al. 2012) when patients still gain from the acoustic input (Dooley et al. 1993; Armstrong et al. 1997; Ching et al. 2004; Potts et al. 2009). When the nonimplanted ear does not provide any benefit despite acoustic amplification, bilateral cochlear implantation is the alternative suggestion (Tyler et al. 2003; van Hoesel & Tyler 2003). Many studies have shown the

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benefits of bimodal rehabilitation (Ching et al. 2004; Firszt et al. 2008; Potts et al. 2009; Sucher & McDermott 2009) or bilateral cochlear implantation (Nopp et al. 2004; Schleich et al. 2004; Long et al. 2006; Litovsky et al. 2009; Loizou et al. 2009; van Schoonhoven et al. 2013) as compared with monaural listening with only one cochlear implant (CI). However, what the best solution would be between bimodal rehabilitation and bilateral cochlear implantation for each particular patient remains a difficult clinical decision. CI candidates with equivalent unaided hearing thresholds may display different aided threshold and speech understanding benefits (Olson & Shinn 2008; Ching et al. 2009). Evidence for which solution should be preferred for what amount of residual hearing is lacking.

So far, no random-based trial with appropriate controls comparing bimodal rehabilitation or bilateral implantation has been conducted, and perhaps it is next to impossible to propose such a study from an ethical point of view. Several studies have compared samples of patients from the two groups, but none managed to find a clear predominance of one binaural rehabilitation choice over the other (Ching et al. 2009; Cullington & Zeng 2011; van Schoonhoven et al. 2013). The major limitation may have been the limited number of subjects tested, not enabling sufficient statistical power.

In the present study, we address the issue of number of subjects by analyzing the data from a large sample of CI users collected from multiple CI centers. More specifically, we aimed to analyze the speech performance in quiet and in noise for 2247 CI recipients from 15 international clinics, with speech scores collected in their usual listening modes, that is, monaural listening (one CI alone), bimodal listening (CI/HA), or bilateral CI listening (CI/CI). It should be noted that the testing conditions were routine speech audiometry tests, with no source separation of speech and noise in most of the centers (Table 1). This may have biased the results of this study in favor or disfavor of either the bimodal or bilateral condition.

Because the bilateral CI sample was also relatively large (n = 86) compared with other studies on bilateral implantation, a second objective of the present study was to find predictors for the better ear among routinely available data from the clinics and understand why differences in speech intelligibility between the two implanted ears may be observed. We aimed to understand how some clinical factors may influence central reorganization of speech processing and to find clues to choose the better ear to implant in case of unilateral CI. For example, in one study of simultaneous bilateral implantees (n = 27), asymmetric results (speech score differences >20% between the two ears) were observed in 40% of patients (Mosnier et al. 2009). So far, there is no explanation for these differences. In accordance with the concept of asymmetric central speech processing resulting in a right ear advantage for speech (Zatorre & Belin 2001; Abrams et al. 2008; Formisano et al. 2008; Henkin et al. 2008; Poeppel et al. 2008; Zatorre & Gandour 2008), we first looked for a beneficial effect of implanting the right ear in terms of speech understanding, in the case of monaural listening (one CI alone). Secondarily, because the right ear advantage for speech in the nonimplanted population may increase with age (Martin & Jerger 2005), further analyses were performed on the subsample aged 50 years and more. Finally, because clinical factors such as duration of severe-to-profound hearing loss (s/p HL), age at onset of s/p HL, etiology, duration of CI experience, and residual unaided pure-tone average (PTA) may influence speech performance (Blamey et al. 1996, 2013), these factors were factored out in a further analysis exploring a side advantage in speech intelligibility.

TABLE 1. Matching between raw preoperative aided speech scores and a percentile ranking of 60%

Tests in Q (Type, Presentation Level in dB SPL, Name, and Language)	Tests in N, SNR in dB, Type	Mean Score (% ± SD) in Q, in Each Center	Score (%) Matching With a Preoperative Ranked Score of 60%	% of Subjects: CI, CI/HA, and CI/CI in Q, in Each Center
Dis words at 60 dB (Fournier, French)	Sent, SNR 10, cocktail party	16 ± 20.1	20	59/25/16
Dis words at 60 dB (Fournier, French)	Sent, SNR 10, cocktail party	20 ± 22.4	20	36/56/8
Dis words at 60 dB (Fournier, French)	Dis w, SNR 10, cocktail party*	15 ± 16.4	20	56/44/0
Monos words at 65 dB (Lafon, French)	Dis w, SNR 10, speech noise*	10 ± 14.4	10	88/9/3
Monos words at 70 dB (NVA, Dutch)	Mono w, SNR 10, speech noise	30 ± 23.0	35	97/3/0
Monos words at 70 dB (NVA, Dutch)	Mono w, SNR 10, speech noise	27 ± 25.8	32	77/20/3
Monos words at 70 dB (NVA, Dutch)	Sent, adapt SNR, speech noise	17 ± 20.3	24	89/11/0
Monos words at 70 dB (Polish)	Mono w, SNR 10, pink noise	5 ± 11.6	5	65/35/0
Phonemes at 65 dB (CNC, English)	Sent, SNR 10, pink noise	32 ± 22.7	39	64/32/4
Phonemes at 75 dB (CVC, Dutch)	Phon, SNR 10, speech noise	17 ± 14.8	20	72/27/1
Phonemes at 70 dB (Lafon, French)	NA	16 ± 22.9	16	37/51/12
Sentences at 70 dB (BKB, English)	Sent, SNR 10, pink noise	17 ± 24.9	12	99/0/1
Sentences at 70 dB (BKB, English)	Sent, SNR 10, pink noise	14 ± 19.6	12	100/0/0
Sentences at 60 dB (HINT, French)	Sent, SNR 10, speech noise	29 ± 26.6	45	79/13/8
Sentences at 70 dB (TAM, French)	Sent, SNR 10, speech noise	14 ± 19.8	8	87/11/2

This table shows the tests used in each center in quiet (Q) and in noise (N). The normal-hearing population tends to score 100% on these tests. The third column displays the mean preoperative performance (±SD) of all CI candidates in aided condition in free field, in one center. The means vary among centers using the same test because of different populations and CI indications. The fourth column shows the scoring for one test in a given center, which corresponds to a preoperative ranked score of 60%. The 60% ranking may be lower than the mean if the population was composed of a large number of very poor performers and some very good performers improving the mean. The fifth column displays the relative proportion (%) of subjects in each group in each center. Depending on the test a clinician uses and the clinical profile of the population studied, he may be able to identify those CI candidates who may benefit from bimodal listening if they perform as well as the score indicated in the fourth column.

*Signal and noise were always presented at 0°, except when *, where signal and noise were separated from 90°. Cocktail party masking noise is a French standardized masking noise representing the background noise heard in a restaurant room (babble).*

adapt, adaptive; CI, cochlear implant; Dis words, dissyllabic word test; HA, hearing aid; Monos words, monosyllabic word test; NA, not available; Phon, phonemes; Sent, sentences; SNR, signal-to-noise ratio.

MATERIALS AND METHODS

In this project, approved by the Royal Victorian Eye and Ear Hospital Human Research Ethics Committee (Project 10/977H, Multicenter study of cochlear implant performance in adults), data from 15 centers in Australia, Europe, and North America were gathered. This dataset was the same as used in the studies of Lazard et al. (2012b) and Blamey et al. (2013).

Retrospective data from 2251 adult CI recipients implanted between 2003 and 2011 were collected. To ensure postlingual deafness in a strict sense, the onset of s/p HL was required to be after the age of 15 years. The onset of s/p HL was defined as the age from which the patient could no longer use hearing alone to communicate (i.e., without lipreading), even with the best-fitted HAs, and/or understand TV, and/or stopped using the telephone. Each center provided data from at least 100 CI recipients who fit the inclusion criteria.

Speech perception scores in quiet and in noise were collected in patients' usual listening mode in each center, following routine clinical procedures (see Statistical Analysis section for more details about comparing all patients from different centers). These listening modes were either one monaural condition with one CI but without any other auditory assistive device on the contralateral side (CI alone), one bimodal condition with one CI on one side and one HA on the other side (CI/HA), or one bilateral condition with one CI on each side (CI/CI). Patients were only assigned to one participant group with no overlap: subjects tested with a contralateral HA were not the same ones tested with their CI alone or with two CIs if sequentially implanted. We did not perform within-subject comparison (i.e., monitoring outcome modifications in CI/HA subjects becoming CI/CI). Furthermore, because there were only four patients implanted with hybrid electroacoustic devices (capable of stimulating electrically and acoustically in the same ear), these four subjects were excluded from the present study. Thus, the number of subjects included in each subgroup was as follows: CI alone: n = 1572; CI/HA: n = 589; and CI/CI: n = 86.

Two postoperative speech-intelligibility scores for each recipient were requested from the clinics: one collected early after the activation (T1) and one collected later on (T2). The choice of the date of the tests was free and varied between and within centers. The mean and standard deviation were 0.5 and 0.8 years for T1, respectively, and 2 and 1.7 years for T2, respectively.

Other clinical variables such as duration of s/p HL, age at onset of s/p HL, etiology, duration of CI experience, unaided PTA thresholds (mean of unaided residual hearing levels in decibels measured at the test frequencies of 500, 1000, and 2000 Hz) before implantation, and aided preoperative speech scores in free field were also available for most of the subjects. These factors were used in the analysis of the results, as they were previously shown to contribute to variability in speech-intelligibility performance with a CI (Blamey et al. 1996, 2013; Lazard et al. 2012b).

Statistical Analyses

Similar to Blamey et al. (1996, 2013) and Lazard et al. (2012b), a percentile-ranked score for each patient within each center was calculated from the raw speech test scores measured preoperatively and postoperatively. Percentile ranking was used as a way of normalizing data as the tests were conducted in different languages, presented at different levels, and tested with different noise conditions across the centers. However, all the patients from each specific center were tested with the same speech material and in the same conditions. Using ranking thus removes differences in clinics' practices without removing the relative differences between patients within a specific clinic, with the distribution of the rankings varying uniformly from 0 to 100%. Preoperative aided speech scores (i.e., with best-fitted HAs) were also ranked within each center, but independently of postoperative scores. The postoperative performances obtained in the three modes (CI, CI/HA, and CI/CI) were pooled and ranked within each center, enabling meaningful comparison of the outcome across these three modes. Performances in quiet and in noise were ranked separately.

In the study of Blamey et al. (2013), a four-factor unbalanced analysis of variance (ANOVA) using a general linear model (GLM; Minitab version 12) was described and used to define clinical predictors of speech outcomes in adult unilateral CI recipients. The four independent factors were duration of s/p HL, age at onset of s/p HL, etiology, and duration of CI experience (calculated by subtracting the date of testing and the date of first activation). When variables were continuous, factors were partitioned into ranges. Duration of s/p HL was defined as the time in years between the onset of s/p HL and the date of implantation. The ranges for duration of s/p HL were 0 to 4, 5 to 9, 10 to 14, 15 to 19, 20 to 24, 25 to 34, 35 to 44, and over 45 years. Age at onset of s/p HL was split into the ranges 15 to 29, 30 to 39, 40 to 49, 50 to 59, 60 to 69, 70 to 79, and 80 or over years. Etiologies were grouped into 15 different classes (see Blamey et al. 2013 for details). Duration of CI experience was divided into the ranges 0 to 5, 6 to 11, 12 to 23, 24 to 35, 36 to 47, and over 47 months. In the present study, the listening mode (CI, CI/HA, and CI/CI) was added to the model, as a new factor, resulting in a five-factor unbalanced ANOVA to compare speech perception outcomes across these three listening modes. For continuous variables not entered into the GLM used by Blamey et al. (2013), such as PTA, correlations with the entire dataset of ranked speech scores were secondarily tested using Pearson's correlation test. Ranked preoperative aided speech scores were entered into one-way ANOVAs (with post hoc Tukey tests) evaluating their influence within each subgroup of listening mode. For all the analyses, the dependent variables entered were the speech performance percentiles measured at T1 and T2. These scores were considered independent scores for the same patient for added statistical power, as Lazard et al. (2012b) and Blamey et al. (2013) showed that choosing the mean of these two scores or one of these two scores randomly did not affect the global results. A value of $p \leq 0.001$ was considered significant because of the large numbers of data points in this study. Factors with p values in the range 0.001 to 0.05 were considered to be marginally significant (as described in Lazard et al. 2012b; Blamey et al. 2013).

A second aim of this study was to explore the potential factors that produce the asymmetric speech scores observed in some cases of bilateral implantation. A side advantage (whether implanting the right or left side gave better results) was first examined on the whole sample (n = 2251, the four subjects with hybrid stimulation were not excluded) in quiet in the monaural condition (one CI alone). When patients had bilateral sequential implantation, the speech scores for the first implanted ear were selected. In the case of simultaneous implantation, the speech scores for the right implanted ear were selected (arbitrary decision). A one-way

ANOVA was performed taking into account the implanted side: right/left (R/L). Handedness could not be included in the analysis because this variable was available for only 342 patients. Secondarily, because the right ear advantage for speech in the nonimplanted population may increase with age (Martin & Jerger 2005), three additional different and independent one-way ANOVAs studying the effect of the implanted side were performed on age subgroups (≥55, >60, and >70 years). Finally, a GLM including the four "usual" factors (duration of s/p HL, age at onset of s/p HL, etiology, and duration of CI experience) (Blamey et al. 1996, 2013), plus the residual PTA of the better ear (in ranges) and the side of implantation was performed (six-factor GLM). PTA of the better ear was chosen because it was shown in the study by Lazard et al. (2012b) that implanting the better or the worse ear did not have any influence on outcome. It was further shown that having useful auditory inputs before implantation improved postoperative outcomes with the CI (Lazard et al. 2012b). Using a GLM enables factoring out the influence of the independent factors studied in the analysis. Thus, this analysis looked for an ear advantage after factoring out the potential role of the other factors included in the same analysis. This six-factor GLM analysis was performed with speech scores in quiet and in noise separately, obtained with one CI alone in the 2251 subjects.

Among the total of 2251 patients included, 86 patients were implanted and tested bilaterally. More statistical analyses were performed on this subset of the sample. For each subject, speech scores in quiet were compared between the two CIs, tested separately. When scores presented a difference of more than 10%, a better side (R/L) was determined (this rather strict criterion was applied to improve the chance of obtaining significant differences). In case of sequential implantation, the comparison between the two ears was done with scores collected at similar time delay from the date of surgery. A binomial distribution was performed to test a side advantage. Chi-square tests with Yates correction, or Fisher exact tests when the number of data were small, were used to test event frequencies of duration of s/p HL, duration of total HL (defined as the time delay between the onset of moderate HL and the date of first surgery), side implanted first in case of sequential implantation, amount of residual hearing based on PTA before surgery (PTA of the better ear), and use of HAs.

RESULTS

Ranked Preoperative Aided Speech Scores

Mean ranked preoperative aided speech scores were 44% (standard deviation ±29.0) for the CI-alone group, 62% (±29.7) for the CI/HA group, and 42% (±9.1) for the CI/CI group. The CI/HA group performed significantly better than the other two groups in terms of aided preoperative speech scores (ANOVA with post hoc Tukey tests: $p = 0.001$). Table 1 shows for each center what ranking represents. For example, in the last center, the average preoperative score was 14% correct response during a sentence test for all subjects (CI, CI/HA, and CI/CI), and a ranking of 60% corresponded to 8% correct response. The notion of ranking is illustrated in Figure 1. For this center, about 40% of patients scored more than 8% on the preoperative speech test with HAs.

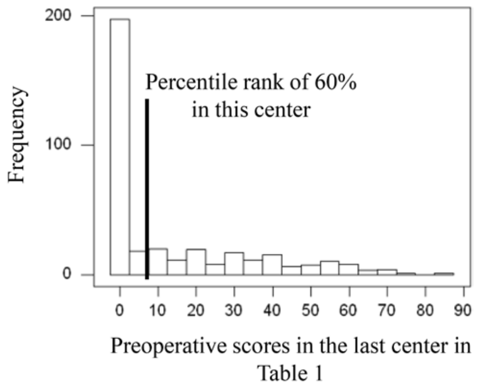

Fig. 1. Illustration of the notion of 60% rank in a given center. The patients scoring better than 8% during the preoperative speech test used in this center (right side of the black line) will benefit from a bimodal listening mode postoperatively.

Differences Among CI, CI/HA, and CI/CI in Quiet

Table 2 shows the relative influence of the independent factors included in the five-factor unbalanced ANOVA. Except for etiology, all factors were significant ($p \leq 0.001$). The relative importance of the factors was the same as in the study by Blamey et al. (2013), in which the analysis was performed on ranking of speech scores in quiet in the monaural mode (one CI alone) for all patients (n = 2251). According to *F* values, the order of factor importance, from most to least, was duration of CI experience, age at onset of s/p HL, duration of s/p HL, and etiology. In the present study, the effect of listening mode in quiet was also found to be important ($F(2, 3137) = 16.77$, $p = 0.0001$). In a GLM analysis, residual percentile ranking represents the effect of the factor studied after factoring out the possible effects of the other factors included in the analysis. Thus, Figure 2 shows the mean residual percentile ranking of each listening mode in quiet. The numbers next to the means indicate the numbers of data points within each mode (speech performance in quiet at T1 and T2) entered in the analysis. On average, a progressive increase in performance was observed across the listening modes from CI to CI/HA and eventually to CI/CI. The mean difference between the two extremes (CI versus CI/CI) was 11%. Patients with one CI alone performed significantly more poorly than patients tested in either binaural mode (CI/HA and CI/CI). The difference between the modes CI/HA and CI/CI was also significant in favor of the CI/CI mode, but with a small advantage of 5%. A 5% difference in ranking corresponds to about 3 to 10% in speech score depending on the center and the speech test used for evaluation.

Because bimodal outcomes were reported to be related to PTA of the nonimplanted ear (Waltzman et al. 1992), ranked postoperative speech scores in quiet of patients in the CI/HA mode were plotted according to the residual unaided PTA of the HA side (Fig. 3). The correlation was not significant according to our criteria ($p = 0.006$), and the slope of the regression line was very small ($r = -0.096$), showing that residual unaided PTA of the HA side might not be a reliable clinical predictor of bimodal outcomes.

Outcomes were then studied relative to ranked preoperative aided speech scores. Further one-way ANOVAs with post hoc Tukey tests were performed comparing the profile of ranked preoperative aided speech scores with the postoperative scores for each listening mode in quiet (Fig. 4). Note that the preoperative and postoperative rankings were performed separately: for this reason, a ranking of 50% does not represent the same performance in speech understanding (cf., Table 1 about preoperative speech scores). Postoperative ranked speech scores were

TABLE 2. Results from the five-factor GLM analysis with postoperative speech scores in quiet as dependent variable

Factor	Degree of Freedom	Sum of Squares	Mean Squares	*F*	*p*
Duration of CI experience	5	81,624.6	15,863.9	20.92	0.000
Age at onset of s/p HL	6	74,246.2	15,615.0	20.59	0.000
Listening mode	2	25,434.8	12,717.4	16.77	0.000
Duration of s/p HL	7	75,489.6	9846.1	12.99	0.000
Etiology	14	29,091.5	1717.2	2.26	0.005
Error	3140	2,380,873.6	758.2		
Total	3174	2,666,760.2			

Factors are ordered according to decreasing F values.
CI, cochlear implant; GLM, general linear model; s/p HL, severe-to-profound hearing loss.

highly dependent on preoperative ranked speech scores in the two first modes, but not in the CI/CI mode ($F(4,2406) = 26.8$, $p < 0.0001$; $F(4,813) = 26.3$, $p < 0.0001$; and $F(4,124) = 3.4$, $p < 0.01$, respectively). It is possible that the effect of preoperative ranking for the CI/CI group did not reach the significance level of $p < 0.001$ because of the smaller number of data points in this subset. For both CI-alone and CI/HA groups, results showed that presenting with aided preoperative speech ranking inferior to 60% (cf., Table 1 and Fig. 1) resulted in postoperative outcome below 50%. The postoperative speech ranking means for the preoperative range 60 to 79% were also the same for both groups (54%). However, the increase in postoperative performance was significant from the preoperative speech ranking ranges 60 to 79% and 80 to 100% with respect to lower ranges in the CI/HA group, but not in the CI-alone group (Fig. 4). On average, the CI/CI group performed better than 50% irrespectively of preoperative scores (even in the preoperative speech score ranges below 60%).

Differences Among CI, CI/HA, and CI/CI in Noise

The same five-factor unbalanced ANOVA as in quiet was performed using the ranking of postoperative speech scores measured in noise as the dependent variable (Table 3). The relative importance of each factor was different from the results in quiet. The factor with the major influence was the listening mode ($F(2, 1906) = 26.89$, $p < 0.0001$). CI experience had less importance than in quiet ($F(5, 1906) = 6.60$, $p < 0.0001$). Etiology was not significant ($p = 0.1$). The mean ranking of each listening mode in noise is represented in Figure 5, as well as the number of data points used for the analysis, within each mode, when CI recipients were tested in noise. The overall number of data points is smaller than in quiet because not all subjects were tested in noise (see Discussion for a possible bias in the recruitment of these subjects). The order in terms of speech outcome in noise from the poorest to the best scores across the three listening modes was the same as in quiet: CI alone, then CI/HA, and CI/CI. The difference between the two extremes was 16%. The performance in each mode in noise was significantly different; the patients in the CI/CI mode performing on average 7% better than those in the CI/HA mode.

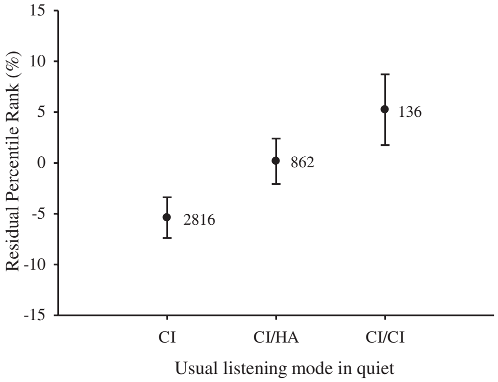

Fig. 2. Significant effect of the type of auditory rehabilitation on postoperative outcome in quiet. Error bars indicate ±2 standard errors of the mean for each listening mode (approximately equivalent to the 95% confidence interval for each mean value shown on the graph; if two mean values fall within one error bar, then the means are not significantly different [$p > 0.05$]). The numbers next to each symbol indicate the number of data points (T1 and T2) in that mode used to perform the analysis. CI is monaural listening with one CI, CI/HA is bimodal listening, and CI/CI is bilateral implantation. CI indicates cochlear implant; HA, hearing aid.

Explanations of Asymmetric Results in Case of Bilateral Cochlear Implantation

The one-way ANOVA including the 2251 patients (1197 right sides, 1034 left sides, and 20 missing data) did not show any side advantage in case of monaural testing with one CI alone in quiet ($F(1,3758) = 0.94$, $p = 0.33$). No such effect was found in case of aging for the subgroups ≥55, 60, or 70 years ($p = 0.24$, 0.12, and 0.75, respectively). The six-factor GLM analysis also failed to show a side advantage while factoring out residual hearing and duration of s/p HL in particular, in quiet ($F(1, 2983) = 1.68$, $p = 0.20$) and in noise ($F(1, 1695) = 1.42$, $p = 0.23$).

To reliably compare speech intelligibility between the two sides (better/poorer ear), 83 patients of the 86 (55 sequential bilateral implantations and 28 simultaneous bilateral implantations) were selected because the delay between the surgery

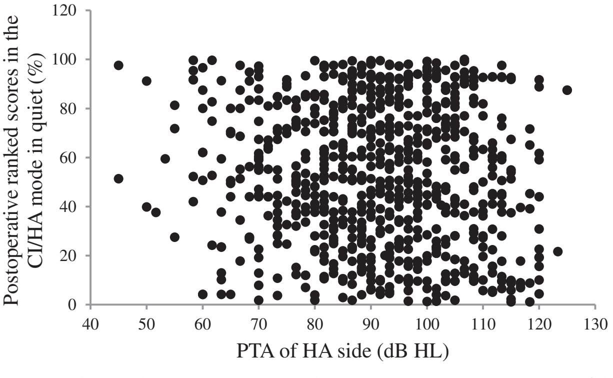

Fig. 3. Weak correlation between unaided pure-tone averages (PTAs) of the nonimplanted side using a hearing aid (HA) in the CI/HA group and ranked postoperative speech scores in quiet. CI indicates cochlear implant.

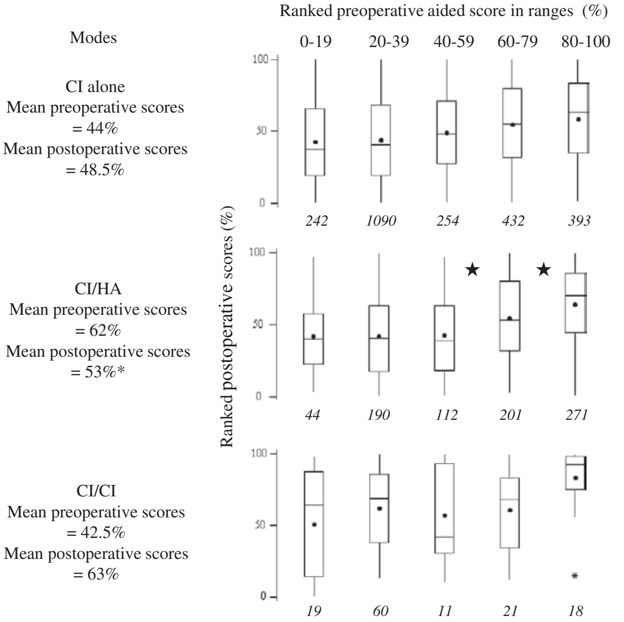

Fig. 4. Box plots of analyses of variance of ranked postoperative speech scores according to ranked preoperative aided speech scores for each listening mode separately. The ranked preoperative aided speech scores are partitioned into five ranges (report to Table 1 to estimate raw scores). Lower italic numbers indicate the number of data points (at T1 and T2) within each range. Horizontal lines within the boxes represent the medians, and black dots represent the means. Black stars correspond to a significant difference between two ranges according to post hoc Tukey tests ($p = 0.05$). In the CI/HA group, the postoperative mean scores corresponding to the last two ranked preoperative ranges were significantly different from each other and from the three lower ranges. *Preoperative and postoperative speech scores were ranked separately. The means cannot be compared directly as they do not represent the same ranking. These means do not indicate that bimodal listeners performed more poorly after implantation than before. These results indicate that, preoperatively, the patients included in the CI/HA group performed better than the other patients. Postoperatively, they did not. CI indicates cochlear implant; HA, hearing aid.

and the testing was similar between each side. Using a binomial distribution, it appeared that the numbers of right (n = 40) or left (n = 36) sides in our sample were within the range of equal probability. This means that no side of implantation was related to a better outcome in the bilateral CI sample. The same evaluation was performed for the subgroups "sequential implantation" and "simultaneous implantation." No effect of side could be evidenced in case of sequential or simultaneous implantations.

Asymmetrical results in cases of sequential implantation were further explored to search an advantage for the side implanted first. The mean percentile rank for the first CI was 80% (±42.2) and 75% (±41.5) for the second CI. These two means were not statistically different (Mann–Whitney–Wilcoxon test: $p = 0.5$).

Contingency tables for event frequencies related to duration of s/p HL, duration of total HL, side implanted first in case of sequential implantation, residual hearing, and HA use before implantation were performed. None of the clinical factors considered was significantly linked to a side advantage.

DISCUSSION

The aim of this study was to address two questions of present-day CI indications for postlinguistically deaf adults: (1) Whether bimodal (CI/HA) or bilateral implantation (CI/CI) provides better outcomes? (2)Whether available clinical data help to explain asymmetric performance in bilateral implantation?

Bimodal Versus Bilateral: Slight but Significant Advantage of the CI/CI Mode for Patients With Low Preoperative Speech Scores

The three CI groups were significantly different from one another for speech perception in quiet and in noise (Figs. 2 and 5). These results from retrospective data confirmed that binaural listening provides better outcome than listening monaurally with one CI (Most et al. 2012), especially in noise (Ching et al. 2004; Ricketts et al. 2006; Dunn et al. 2010). It was also confirmed that the benefit of binaural listening compared with one CI alone was greater with a second CI than with an HA on average (Litovsky et al. 2006), especially in noise in the present study (+6% for the CI/HA group versus +11% for the CI/CI group in quiet, and +9% for the CI/HA group versus +16% for the CI/CI group in noise). A small but significant advantage of one binaural mode over the other one was evidenced: speech rankings in quiet and in noise in the CI/CI mode were slightly, but significantly, better than in the CI/HA mode (+5% in quiet, +7% in noise). Caution is required in interpreting these results because 5 or 7% ranking may represent a nonmeaningful difference in some centers (cf., a 5% difference in ranking may correspond to about 3% difference in speech score in some centers). Table 1 may assist centers to understand how this result applies to their evaluation and clinical population. A second point to stress is that no within-subject comparison was possible to evaluate the benefit of an HA relative to the benefit of a second CI in the same subject. Groups were independent as indicated in the Materials and Methods section.

Previous studies did not demonstrate such an advantage of the bilateral mode, even in difficult listening situations (Litovsky et al. 2006; Cullington & Zeng 2011). However, Cullington and

TABLE 3. Results from the five-factor GLM analysis with postoperative speech scores in noise as dependent variable

Factor	Degree of Freedom	Sum of Squares	Mean Squares	*F*	*p*
Listening mode	2	41,345.6	20,672.8	26.89	0.000
Age at onset of s/p HL	6	58,061.1	10,900.6	14.18	0.000
Duration of CI experience	5	13,004.9	5070.8	6.60	0.000
Duration of s/p HL	7	29,203.5	3664.6	4.77	0.000
Etiology	14	17,504.6	1152.4	1.50	0.103
Error	1906	1,465,469.9	768.9		
Total	1940	1,624,589.7			

Factors are ordered according to decreasing F values.
CI, cochlear implant; GLM, general linear model; s/p HL, severe-to-profound hearing loss.

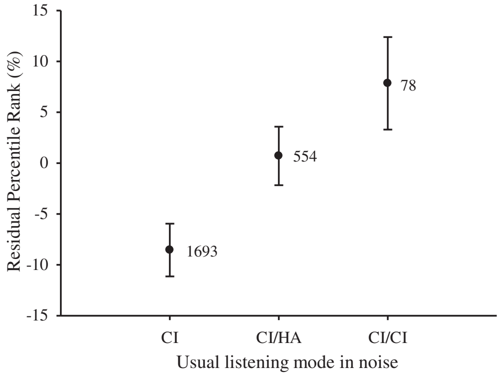

Fig. 5. Significant effect of the type of auditory rehabilitation on postoperative outcome in noise. Error bars indicate ±2 standard errors of the mean for each listening mode (approximately equivalent to the 95% confidence interval for each mean value shown on the graph; if two mean values fall within one error bar, then the means are not significantly different [$p > 0.05$]). The numbers next to each symbol indicate the number of data points (T1 and T2) in that mode used to perform the analysis.

Zeng (2011) included only good performers (word scores in quiet ≥65% for Hearing in Noise Test) when testing CI recipients with a relatively difficult task of pitch identification. In the present study, some subjects in the bimodal group (CI/HA) were observed to perform as well as some bilateral implanted patients (CI/CI), but on average, bimodal listeners performed more poorly. The best bimodal performances were observed for patients with the best HA performance preoperatively, as might be expected.

From the preoperative *unaided* PTA, it was not possible to define an audiometric profile of future good bimodal listeners in quiet (Fig. 3). The average *unaided* residual hearing on the HA side was the same (90 ± 14 dB HL) for the whole CI/HA sample and for those CI/HA subjects who performed better than 60% postoperatively. One study showed that *aided* PTA might be a good potential criterion to choose the type of binaural rehabilitation (Yoon et al. 2012). The present results confirm this trend. Patients benefited from postoperative bimodal listening in quiet if they displayed ranked preoperative aided speech scores better than 60%. In other words, these subjects were the 40% of best performers before implantation (see Fig. 1 to visualize this notion in one given center). Table 1, showing raw results for a selection of routine speech tests, may help practitioners selecting those CI candidates who correspond to this subgroup. The other CI/HA users, with ranked preoperative speech scores below 60%, performed similarly to patients in monaural mode (CI alone) in quiet (Fig. 4). These CI recipients did not benefit significantly from their contralateral HA to understand speech in quiet. Furthermore, in the CI/CI subgroup, outcomes were not dependent on preoperative speech scores. On average, even CI candidates within low preoperative speech score ranges performed better than 50% after implantation (Fig. 4).

However, a few comments have to be made to moderate our findings:

- The difference in favor of bilateral implantation, while significant, was small on average: 5% in quiet and 7% in noise. The clinical relevance of this would depend on the individual centers and their population distribution (Table 1).
- Testing conditions were basic and did not explore specific tasks that may reveal larger HA benefit based on important low-frequency acoustic cues, such as gender/voice recognition, music appreciation, or speech perception in more complex listening environments (Potts et al. 2009; Başkent 2012; Most et al. 2012, Fuller et al. 2014).
- New sound-processing strategies combining acoustic and electric information were not tested in this study (Francart & McDermott 2012).
- The fitting between HA and CI in case of CI/HA may not have been optimal in the present results. Optimization of HA fitting should be tried before proposing a second CI.
- In some countries where some participating centers are located, bilateral cochlear implantation is not reimbursed by the local public health insurance because of an unproven cost-effectiveness (Crathorne et al. 2012). In these countries, encouraging bimodal listening remains the best option.
- From the amount of data available, we were able to obtain statistically significant results, which was an important strength of the present study. However, the retrospective nature of data collection may have caused some bias. For example, we have grouped CI, CI/HA, and CI/CI to the best clinical indications that we could extract from the database. This grouping may have caused some bias as there are no uniform clinical protocols in bimodal and bilateral implantation across multinational centers. As mentioned above, in some countries or clinical centers, bimodal may be the preferred option over bilateral implantation simply due to reimbursement advantages, while bilateral patients may constitute a carefully selected patient population for research purposes (cf., Table 1). Furthermore, the less successful bimodal or bilateral CI users may have stopped using their second device, falling back into the CI-alone group, as suggested by the substantially worse preoperative performance for the CI/CI group than for the CI/HA group. These factors could have contributed to an overestimation or underestimation of performances shown in Figure 1. However, the comparison of preoperative percentile ranks across groups, where the CI/CI group displayed lower average preoperative rank than CI/HA group, and the relatively large number of participants in each group suggest that the CI/CI advantage cannot be purely attributed to biases, but may represent a clinical reality.

In short, the dominant influence of listening mode in noise combined with a loss of relative importance of CI experience (Table 3) confirmed the advantage of the CI/CI mode over the two other modes. It is possible that brain adaptation to difficult listening conditions (noise) rapidly reached a plateau with small potential to improve with CI experience, but that bilateral CI users were favored. The fact that the people tested in noise were presumably the best performers within each group, especially in the CI-alone subjects, may have reduced statistical differences. One meta-analysis showed that CI/CI listeners had “a slight advantage in binaural performance” (binaural squelch effect) over bimodal listeners (Schafer et al. 2011). Moreover, sound-processing strategies aiming to combine electric and acoustic stimulations do not seem to be efficient in noise (Francart & McDermott 2012). Consequently, bilateral CI users seem to be favored especially in noise when testing speech intelligibility. When the two CI sound processors become better synchronized, one can hope that the gain will be even greater (Verhaert et al. 2012).

Everyday Clinical Data Cannot Explain Asymmetrical Results in Bilateral Cochlear Implantation

From the asymmetrical hemispheric functioning of speech processing and its left dominance (see Lazard et al. 2012a for a review), a right ear advantage was sought to answer the question "does implanting the right ear in adults provide better speech understanding?" The analyses did not show any effect of side on speech performance, even at later ages when the right ear advantage for speech may increase (Martin & Jerger 2005). From the literature, the left hemispheric dominance for speech does not seem to be modified by deafness: (1) this hemispheric specialization is preserved in sign language processing (Campbell et al. 2008; MacSweeney et al. 2008); (2) postlingual deaf subjects, even after years of profound deafness, preserve the left dominance for phonology processing (Lazard et al. 2010, 2012c); and (3) lipreading also shares left auditory cortical areas (Calvert & Campbell 2003; Hall et al. 2005; Lazard et al. 2014).

The results of the present study might show that ascending and descending pathways from the cochlear nucleus to the primary auditory cortex reorganize to favor speech transmission to the left hemisphere, whatever the side of worse or better ear (Lazard et al. 2012b). So far, in the case of left implantation, it is not possible to say whether left auditory input uses direct ipsilateral projections from the cochlear nucleus, or whether decussation taking place at higher relays becomes predominant, or both. Similarly, the role played by the efferent medial olivocochlear efferent system (see Lazard et al. 2012a for a review) is unknown in the case of deafness and compensatory reorganization. However, our hypothesis of a nondominant ear in adult CI recipients may not be true in children. Thus, in developing brains of congenitally deaf individuals, a right advantage was shown in speech perception for unilateral implantation (Henkin et al. 2008).

The statistical analyses on the other factors tested (duration of s/p HL, duration of total HL, side implanted first in case of sequential implantation, amount of residual hearing, and use of HAs) also failed to explain the asymmetrical results observed in case of bilateral implantation. Furthermore, the effectiveness of combining information from the two ears is difficult to predict from the monaural results, even in diotic CI/CI conditions. For example, the surviving populations of neurons in each ear (an information not available so far) might not overlap, such that a CI in one ear might fill in the information in a given frequency region that is poorly encoded in the other.

CONCLUSIONS

From the results of this large-scale retrospective study, it was possible to evidence a small but significant difference in terms of speech understanding in favor of bilateral cochlear implantation compared with bimodal rehabilitation (one CI and an HA on the contralateral side). However, the clinical relevance of this result may vary across center, depending on their CI candidate population (e.g., though significant, a 5% difference in some tests does not represent a real gain in everyday life). It seemed that only CI/HA patients with ranked preoperative speech scores >60% (Fig. 4 and Table 1) gained from their HA in the tests performed in this study (speech scores in quiet and noise). However, some important factors for life quality, such as music appreciation (Fuller et al. 2013), were not evaluated here. Despite some bias due to the retrospective feature of this study, these results may be taken into consideration to improve clinical practice.

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